Catalytic Infrared Dehydration of Onions

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ABSTRACT: Dehydrated onions are commonly dried with convection heating, which is inefficient and costly. This study compared the drying and quality characteristics of onion dried with catalytic infrared (CIR) heating and forced air convection (FAC) heating. Sliced high-solids onions were dehydrated under 9 conditions: CIR heating with and without air recirculation, and FAC each operated at 60, 70, and 80 °C. In general, CIR both with and without air recirculation had higher maximum drying rates, shorter drying times, and greater drying constants than FAC at moisture contents greater than 50% (d.b.). Dried onion quality, measured as pungency degradation, was similar for both the drying methods at 60 and 70 °C. The color analysis showed better product color (whiter and less yellow) at lower temperatures for CIR and higher temperatures for FAC. The browning could have been caused by the higher surface heat flux of the CIR heating and longer process times of FAC drying. Aerobic plate counts and coliform counts were not significantly different for either product from the CIR or FAC drying. However, samples dried by the CIR had significantly lower yeast and mold counts than those dried by the FAC. It is recommended that CIR be used in the early stages of onion drying.

Keywords: dehydration, drying, infrared, onion, pungency

Introduction

Onion, an important commercial food product and common household seasoning, is considered the most important spice bulb crop in the world (Pruthi 1980). Onions stored for long periods are subject to storage rot, sprouting, rooting, and loss of water making dehydration necessary (Akbari and Patel 2003). Many breeds of high-solids dehydrator onions are grown for the sole purpose of making dried onion products. In 2001, California produced approximately $\frac{1}{4}$ of all the onions in the United States. Of those produced in California, 66% were storage onions, which are primarily used for dehydration (USDA 2001). Dehydrated onions are normally produced using forced convection tunnel dryers with variable temperatures at different drying states. Convective drying has been researched intensively, but this method has low energy efficiency and drying rate and also adversely affects the quality of the final products (Mazza and LeMaguer 1980; Gowda and others 1986; Elustondo and others 1996; Markowski and Zielonka 1996; Laguerre and others 1999; Adam and others 2000; Akbari and Patel 2003).

Infrared drying offers many advantages over convection drying, including greater energy efficiency, heat transfer rate, and heat flux which results in shortened drying time and higher drying rate (Sandu 1986; Dostie 1992; Navarri and others 1992; Afzal and Abe 1997; Skjoldebrand 2002). Recent introduction of catalytic infrared (CIR) dryers for dehydration of agricultural materials has increased the interest in infrared drying for onion (Macaluso 2001). CIR uses natural gas or propane, which is passed over a mesh catalyst pad to produce thermal radiant energy through a catalytic reaction. This reaction occurs below the ignition temperature of gas so that no flame is produced. The electromagnetic radiant energy from CIR has peak wavelengths in the range of medium to far infrared. The peak wavelengths match reasonably well with the 3 absorption peaks of liquid water, which could result in rapid moisture removal. Because the CIR directly converts natural gas to radiant energy, it is more energy efficient than the typical infrared emitters using electricity. Relatively little literature is available regarding infrared dehydration of onion (Wang 2002; Kumar and others 2005; Sharma and others 2005) and there has been no published research of catalytic infrared dehydration of onions.

Final product quality is very important when evaluating a drying method. High quality dried onion products should be white in color, rehydrate easily, have high pungency, and low microbial loads (Saimbhi and others 1970). The objective of this research was to compare the drying characteristics of thin-layer onion dehydration using CIR drying and forced air convection (FAC) drying with various drying conditions. The studied drying characteristics included the drying rate, drying time, drying constant, and quality of dried onion product. The measured quality characteristics included pungency degradation, color changes, and microbial load reductions.

Materials and Methods

Materials

Southport White Globe onions were supplied by Gilroy Foods Inc. (Gilroy, Calif., U.S.A.) and were representative of onions used in their commercial operation for the 2003 and 2004 seasons. The onions had diameter of 40 to 70 mm and solids content ranged between 24.3% and 29.3%. Moisture content of onion samples was measured according to the American Dehydrated Onion and Garlic Assn. (ADOGA) Official Standards and Methods (1997) (70 °C for 6 h at 26.1 mmHg vacuum). Moisture measurements were performed in duplicate and reported as average on a dry basis unless otherwise mentioned. Onions were cleaned by removing the tops and bottoms along with the outer dry layers and the 1st fleshy layer, which accounted for about 20% of each onion. Onions were sliced perpendicular to the axis into 2.5 ± 0.2 mm thick pieces using an industrial food slicer.

CIR dryer setup

The CIR dryer arrangement (Figure 1) consisted of a drying chamber ($95 \times 65 \times 65$ cm) with a CIR emitter (Catalytic Drying

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Technologies LLC., Independence, Kans., U.S.A.) mounted from the top of the chamber. The sample was placed on a drying tray (84 × 53 cm), which consisted of a fine mesh aluminum screen stretched across a strip steel frame. At the product surface, IR intensity decreased away from the center of the drying tray. When the drying tray was positioned 20 cm below the emitter, the intensity at the tray's center was 4818 W/m^2. Average intensity at 15 points across the tray at this distance was 2226 W/m^2 measured using an Ophir FL205A Thermal Excimer Absorber Head (Ophir Optronics Inc., Wilmington, Mass., U.S.A.). An aluminum waveguide (48 × 30 cm, upper rim; 42 × 22 cm, base perimeter), used to achieve a uniform heating of the entire product, rested on top of the drying tray and surrounded the product. A balance (Ohaus Adventurer Pro; 8 kg capacity, 0.1 g accuracy) was placed beneath the drying tray and measured product weight during drying. A 1/100 HP exhaust fan (Dayton Electric Mnfg.) was located on the top of the drying chamber for ventilation. Two 1/10 HP fans (Dayton Electric Mnfg.) mounted on each side of the dryer were used to recirculate part of the warm air in the drying chamber. These fans pulled air from the top of the drying chamber and fed it back into the chamber through slits running the entire length of the drying chamber.

The CIR emitter was preheated by an electric element located inside the emitter. The natural gas intake was regulated by a gas control valve controlled by a computer system. Two Type-T thermocouples (response time 0.15 s) were used to measure the product temperature. Each thermocouple was placed inside the flesh of an onion slice, which was placed within the innermost 10 cm^2 of the onion bed. The average temperature was used as input to control the product temperature by turning the emitter on or off, which was achieved by opening and closing the gas supply valve of the emitter. For example, the temperature of the emitter surface was 752 ± 22 °C in the early heating stage. It took 8, 11, and 13 min to heat the product to the set temperatures of 60, 70, and 80 °C, respectively, without air circulation. A large amount of moisture had been removed during this drying period. After the product reached the set temperature, the emitter was automatically turned off and the emitter temperature started to decrease. Once the product temperature was below the set temperature, the emitter was turned on again to maintain the product temperature. During the intermittent heating period, because a large amount of moisture had been removed, a relatively small amount of energy was needed to maintain the product tem-

perature. The ratio of emitter on and off time decreased with the increase of moisture removed and drying time. The emitter surface temperature decreased rapidly during the intermittent heating period, which lasts about 20 to 30 min before the emitter temperature was stabilized at about 100 °C. In the temperature control, when the emitter temperature was below 150 °C, the natural gas may not be effectively catalyzed and emitter temperature was maintained by the electric heating unit in the emitter.

Thermocouples and balance inputs were processed by using a data acquisition system, which was developed at Univ. of California, Davis and consisted of a personal computer with Test Point software (Capitol Equipment, Bedford, N.H., U.S.A.).

FAC dryer setup

The FAC dryer used in the tests was an electrically heated column dryer with diameter of 33 cm. A fan powered by a $^3/_4$ HP permanent magnet DC motor (Dayton Electric Mnfg.) blew heated air through an electric coil heater and then through the column. Product was placed in a circular mesh tray near the bottom of the column and suspended by wires to the Ohaus balance to record product weight change during drying. The temperature of heated air was also controlled by the same computer control system as the CIR dryer using a Type T thermocouple to measure the temperature of the air before it reached the product. The on and off cycles of the electric heating coils were controlled automatically to maintain the set point temperature. The air velocity for all of the tests was maintained at 0.5 m/s.

Drying trials

Nine conditions were tested: CIR heating with and without air recirculation, and FAC each operated at 60, 70, and 80 °C. An onion sample, 250 g for CIR and 150 g for FAC, of intact slices was arranged in a single layer on the drying tray at a loading rate of 2.5 kg/m^2. For CIR the drying tray was placed in the preheated CIR drying chamber and the thermocouples were positioned as described above. Distance between the emitter and drying tray was 15 cm with maximum intensity of 4752 W/m^2. CIR drying tests with air recirculation had both the recirculation fans on during the entire test. Average air velocity was set at 0.5 m/s. Each weight point was averaged with the 2 prior and 2 consecutive points to correct for noise. Weight data were also corrected for lift created by air inside the dryers based on the weights with and without air flow. Onion weight and temperature were recorded every 60 s with the aforementioned data acquisition and control system.

Targeted final moisture content (MC) of the dried onion was set at 10% (d.b.) in this study. The final weight of dried onion sample was determined based on the initial and final MC and initial sample weight. The experiments were replicated 2 or more times.

Drying kinetics

Drying rate was calculated in grams of moisture loss per kilogram of initial weight of onion sample per minute (g/kg$_{initialweight}$ min). The exponential model was chosen to describe the drying process. Model curves were fitted to the experimental data and the performance of the model was determined by the correlation coefficient (R^2).

The exponential model is as follows:

$$MR = \frac{M - M_e}{M_0 - M_e} = \exp{[-kt]} \qquad (1)$$

where MR is the moisture ratio; M is the moisture content (% d.b.) at any given time during drying; M_0 is the initial moisture content; M_e

Figure 1−CIR dryer: 1−natural gas; 2−gas flow control; 3−air exhaust; 4−blower; 5−CIR emitter; 6−recirculation warm air; 7−computer controller; 8−wave guide; 9−thermocouple, 10−onion sample; 11−balance

is the equilibrium moisture content; k is the drying constant (h^{-1}); and t is time in h.

Moisture ratio (MR) was determined using the moisture content data collected in the drying experiments. The fixed 4% (d.b.) equilibrium moisture content (EMC) was estimated from findings in literature (Wang 2002). For each drying condition, MR data were plotted on semilogarithmic axis versus the time (h) and the slope of the fitting line was the constant k. Correlation coefficients, means, and standard deviations were also calculated for all 9 drying conditions.

Quality tests

Pungency. The effect of drying on pungency was determined with 4 trays each containing 40 g of sliced onions, which were dried simultaneously. Trays were removed at 10, 20, 30, and 40 min for 80 °C experiments; 10, 20, 40, and 60 min for 70 °C experiments; and 30, 60, 120, and 180 min for 60 °C experiments. These times correspond to the approximate times that were required to achieve a 10% MC (d.b.) at each temperature. After removal, sample weight was measured and corresponding MC was calculated. Deionized water was added to the dried products until the total weight of water plus product was 90 ± 1 g. After rehydrating for 5 min, the samples were homogenized for 30 s at 7000 rpm and 30 s at 10000 rpm using a hand-held homogenizer (Bahmix Bio-Mixer, Bartlesville, Okla., U.S.A.). Slurries were held for 30 min at room temperature before filtering through 2 layers of cheesecloth.

Pungency was measured using a chemical pyruvic acid assay outlined by Anthon and Barrett (2003). Filtrate (25 μL), deionized water (1.0 mL), and 1.0 mL of 0.25 g L^{-1} DNPH in 1 M HCl were placed in 13 mm × 100 mm test tubes, and tubes were heated in a 37 °C water bath for 10 min. Upon removal, 1.0 mL of 1.5 M NaOH was added. Absorbance at 515 nm was measured on a Beckman DU 7500 spectrophotometer. Inherent, nonenzymatically formed pyruvate was measured after heating a fresh 40-g sample in an 800 W microwave oven for 1 min. Standards were prepared by adding 25 μL of sodium pyruvate solution in concentrations of 0, 2, 4, and 8 mM instead of the onion filtrate. Enzymatically formed pyruvate was calculated from the difference between the amount of total pyruvate and the nonenzymatically formed pyruvate. The average results of duplicate tests were reported as percentage losses in pungency from a fresh onion sample at various moisture contents.

Color measurement and microbial load reduction tests. L and b color measurements of Lab color were performed for milled dried onion samples from the drying rate trials using a Minolta CM-508 spectrophotometer. The a measurement was not reported because it is not often used to indicate dried onion quality. The average of 5 readings from each sample was reported.

For determining the microbial load reduction, six 50 g sliced samples were dried with CIR and FAC at 60, 70, and 80 °C to 10% MC. Dried sample (10 g) was stored for 5 d. The sample was added to a 90 mL Butterfield's buffer dilution blank and allowed to rehydrate for 10 min at 4 °C. Sample was homogenized for 1 min in a stomacher blender (Stomacher 400, Seward, Thetford, U.K.) and serial dilutions were made and plated on Tryptic Soy Agar (TSA) (Difco, Becton Dickinson, Sparks, Md., U.S.A.)) for aerobic plate counts, Dicholroan Rose Bengal Chloramphenicaol agar (DRBC, Difco, Becton Dickinson) for yeast and mold counts, and Coliform Petrifilm (3M, St. Paul, Minn., U.S.A.) for coliform counts. Duplicates of each dilution were made. TSA and Coliform Petrifilms were incubated at 35 °C for 24 ± 2 h. DRBC plates were held at room temperature (24 ± 2 °C) for 5 d. The average results from duplicate test samples were recorded as colony forming units (CFU)/10 g dried sample. The tests were performed in duplicate.

Statistical analysis

Data from the quality test experiments and drying times were statistically evaluated in Excel using the t test with the assumption of equal variances. The pungency values for FAC and CIR were compared at each time interval for each temperature. Any value that was statistically significant ($P < 0.05$) is indicated in Table 2. The measured color results were compared for all 3 drying methods and any method that was significantly different was indicated in Table 3.

Results and Discussions

Drying rates and kinetics

Drying rates. When the drying rates were calculated and plotted against moisture content (Figure 2) for each of the 3 drying temperatures, the CIR tests showed much higher drying rates throughout the course of drying than the FAC drying before the MC reached
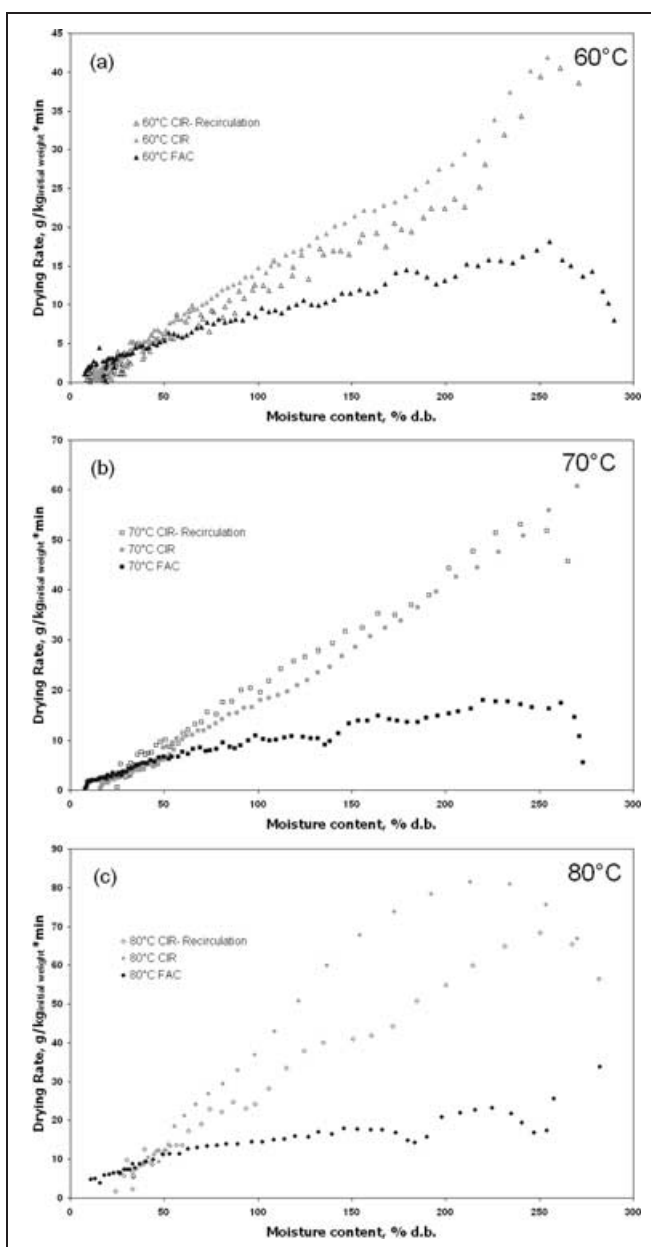
Figure 2 — Drying rates of different drying methods and conditions at various drying temperatures: (a) 60, (b) 70, and (c) 80 °C

Table 1 – Result summary of onion drying characteristics

Drying condition	Drying time to reach 50% MC (d.b.) (min)	Max drying rate (g/kg$_{initialweight}$ min)	Drying constant k (h^{-1})	Correlation coefficient (R^2)
60 °C CIR–recirculation	54.5 ± 7.8	46.9 ± 8.4[a]	1.88 ± 0.42	0.988
70 °C CIR–recirculation	32.0 ± 1.0[a]	59.9 ± 4.2[a]	3.23 ± 0.39	0.995
80 °C CIR–recirculation	24.0 ± 4.6[a]	81.5 ± 6.6[a]	4.47 ± 0.67	0.997
60 °C CIR	47.3 ± 7.5	47.5 ± 10.5[a]	2.04 ± 0.24	0.992
70 °C CIR	36.5 ± 7.8[a]	67.7 ± 9.2[a]	2.87 ± 0.83	0.991
80 °C CIR	18.0 ± 2.8[a]	83.4 ± 4.6[a]	5.95 ± 1.25	0.991
60 °C FAC	56.0 ± 8.5	20.7 ± 3.1	2.23 ± 0.26	0.927
70 °C FAC	51.0 ± 1.4	23.9 ± 3.9	2.45 ± 0.16	0.937
80 °C FAC	33.0 ± 5.7	43.2 ± 22.1	3.82 ± 0.94	0.844

[a]Significantly different ($P < 0.05$) when compared to FAC value at same temperature.

50%. Below this moisture content the decreased drying rates for CIR drying could be due to lower moisture transfer rate in the onion slices for the CIR than the FAC. The air flow might help with the moisture removal at the low moisture range. Increasing the drying temperature in the CIR drying trials increased the drying rate. A minimal increase in drying rate was noted for FAC drying as air temperature was increased.

It is apparent that air recirculation in the CIR drying caused lower drying rates, especially for the 60 and 80 °C trials although an slight increase was seen in the 70 °C trial. The recirculation of warm air did not improve the drying rate under CIR drying as expected. Recirculation air decreased the drying rate and increased drying time, which has been reported by Sandu (1986) and Paakkonen and others (1999).

Drying rates changed with the drying temperature as expected. For each of the plots from the CIR drying tests there was an absence of or just a very brief appearance of a constant rate period because onions are hygroscopic and hygroscopic foods tend to quickly enter the falling rate period (Rahman and Perera 1999). Additionally, surface drying may occur more rapidly with CIR drying, which results in quicker entrance to the falling rate period due to slow water diffusion to the surface of the onion. It is similar to many other foods that do not exhibit a constant rate-drying period due to the colloidal and hydrophilic nature (Mazza and LeMaguer 1980; Baker 1997).

The FAC drying tests showed more of a distinct constant rate period at each of the 3 temperatures tested although the 80 °C rate period was not as profound as the other 2 temperatures. This might be due to the lower heat flux, which resulted in a longer time to reach the critical moisture content. Almost all of all tests showed linear relationships between the drying rates and moisture contents for the period of moisture content from 50% to 225% (d.b.).

Based on the drying rate results, IR drying is recommended to dry onion until about 50% MC, then followed by FAC drying in the latter stage if a combined IR/convection drying system is used for drying onion. For existing drying facilities, IR drying could be considered by adding a unit at the front of current conventional drying systems to take advantage of the high drying rate of IR for improving the overall rate of drying.

The maximum drying rates and times required to reach 50% MC (d.b.) under various conditions are summarized in Table 1. The maximum drying rates of CIR were significantly higher ($P < 0.05$) than that of FAC drying at corresponding temperatures. But no significant difference ($P > 0.05$) was observed between the CIR drying with and without air recirculation at each corresponding temperature.

Drying modeling. Based on the modeling results, the exponential model fits well with the experimental data from CIR drying (Table 1 and Figure 3). The correlation coefficients (R^2) were greater than 0.988. It has been reported that the Page model can be used for
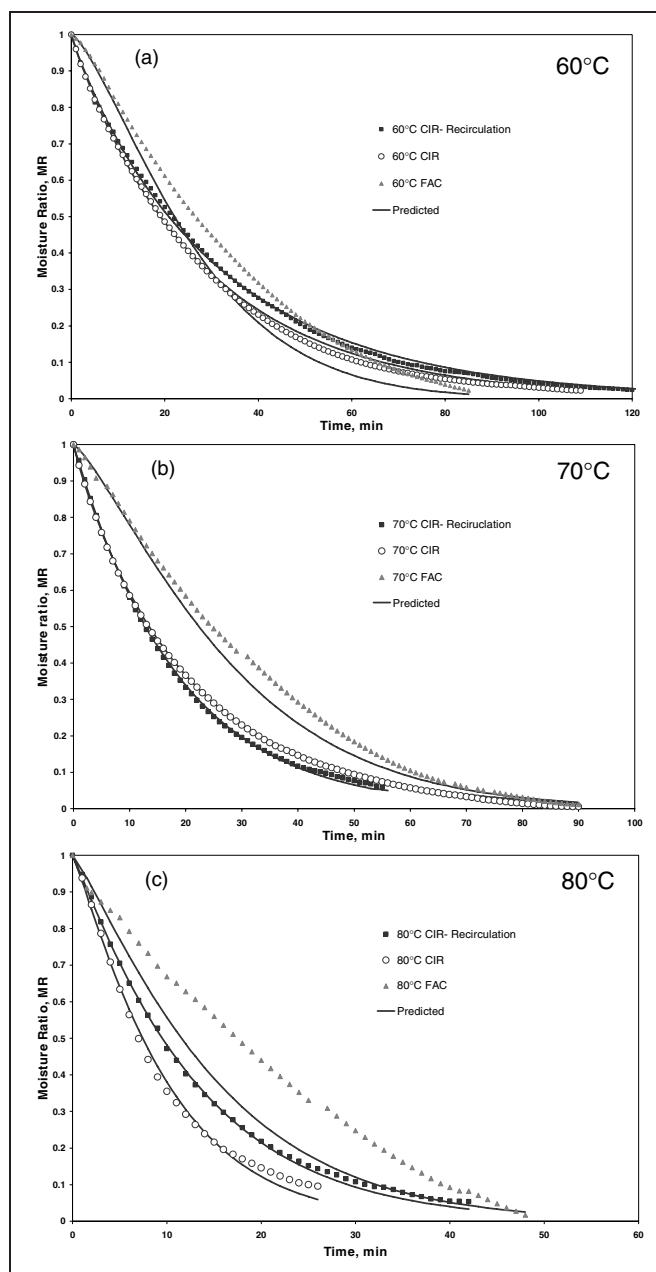

Figure 3 – Predicted and measured moisture ratio at different drying time and temperatures: (a) 60 °, (b) 70 °, and (c) 80 °C

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Table 2 — Pungency changes during drying at different drying temperatures (percent pyruvate of fresh sample). Moisture content is percent dry basis (d.b.).

		Minutes of heating			
		30	**60**	**120**	**180**
60 °C	CIR	89.1 ± 15.7	79.1 ± 3.2	62.4 ± 7.9	59.3 ± 1.0
	Moisture content (%)	142.4	69.2	22.5	14.4
	FAC	80.7 ± 8.5	70.2 ± 3.7	63.9 ± 7.0	65.1 ± 0.4[a]
	Moisture content (%)	106.2	39.3	20.1	15.6
	Unheated sample at 180 min: 99.2 ± 7.2				
		10	**20**	**40**	**60**
70 °C	CIR	86.1 ± 5.4	80.7 ± 19.4	73.6 ± 1.9	83.6 ± 4.9
	Moisture content (%)	135.7	69.5	19.6	15.7
	FAC	115.2 ± 11.2[a]	70.0 ± 17.0	74.9 ± 0.2	74.2 ± 18.2
	Moisture content (%)	148.6	69.3	21	9.7
	Unheated sample at 60 min: 104.0 ± 2.3				
		10	**20**	**30**	**40**
80 °C	CIR	93.7 ± 32.5	69.9 ± 25.0	73.0 ± 6.2	61.3 ± 4.6
	Moisture content (%)	81	30.5	21.1	11.2
	FAC	89.9 ± 20.4	96.2 ± 18.8	97.3 ± 14.8[a]	94.0 ± 3.8[a]
	Moisture content (%)	151.3	73.4	41.6	24.6
	Unheated sample at 40 min: 89.4 ± 2.8				

[a]Significantly greater value ($P < 0.05$) for same time interval and temperature.

modeling the drying characteristics of onions under infrared heating (Wang 2002; Sharma and others 2005). After examining the fitness of the Page model for the CIR drying, it was found that the drying exponents of the Page models were close to 1 and the improvement in correlation coefficients was limited. Therefore, it is concluded that the exponential model can be used to predict reasonably well the drying characteristics of onions under the CIR drying. However, the correlation coefficients of the exponential model for the FAC drying were in the range of 0.844 to 0.927, which indicates that the exponential model may not be an appropriate model for describing the drying characteristics. The predicted and experimental data of the FAC drying in Figure 3 have shown that they did not fit well at the middle of the FAC drying process (Figure 3), which could be due to the long constant rate periods observed. This was most apparent for the 80 °C FAC trial.

Quality of dried onions

Pungency. Both CIR and FAC drying methods had similar trends in pungency changes of onion samples, especially at 60 or 70 °C (Table 2). Pungency of FAC dried samples at the latter drying stage showed a greater decrease at the lower temperatures (60 and 70 °C) when compared to the 80 °C test. This result could be due to longer drying times causing more degradation of the product. The 80 °C test with both drying methods showed that the pungency did not change significantly until the moisture reached approximately 75%. Below 75% MC the pungency of FAC dried samples did not change significantly. This is consistent with the findings of Lee and others (1995), in which high drying temperature had high pungency in the dried onion. It can also be explained that accelerated drying in the initial stages would retain volatiles (Mazza and Maguer 1979; Brewster and Rabinowitch 1990). This is because the volatiles become "locked" into the product when it reaches the critical moisture content.

In general, the pungency of CIR dried samples decreased with moisture reduction. Although the measured pungencies varied with drying conditions and moisture during drying, the pungencies in the samples with the longest drying time and equivalent moisture content were similar, except for the 80 °C trial. The 80 °C trial showed a greater loss in pungency in the samples dried in the CIR, especially at the latter drying stage. This decrease may be caused by the large heat flux delivered to the product and may have resulted in alliinase

inactivation and/or precursor degradation (Brewster and Rabinowitch 1990). Significant color changes were also noted during this time (Table 3).

The large variability of measured pungency results could be caused by nonuniform drying among the samples, difficulties in achieving a homogenous sample, and human error during the assay. Based on the obtained results, if 80 °C drying temperature of CIR drying is used, it is recommended to use it in the early drying stage before the moisture content of the samples reaches 75%. Then low temperature drying can be used in the latter drying stage to prevent severe browning and pungency degradation.

Color. The color measurement results of onion samples with 10% MC are summarized in Table 3. The L values showed a decrease with increasing temperatures for the CIR drying and the opposite effect for the FAC drying. The FAC results were opposite findings from those of Lee and others (1995) where L values decreased with higher air temperatures for convection drying of onion. The low L values for the 60 °C FAC sample may be a result of extended drying time resulting from low drying temperatures. For the CIR drying, a high drying temperature could increase browning and result in a dark color.

The 60 °C FAC dried sample was significantly ($P < 0.05$) less white than either of the CIR samples. Samples from the other drying temperatures are not significantly different from each other. The L color parameter alone may not describe well the color changes occurring during the drying process. The b parameter of the samples was also compared for evaluating the color data in its entirety.

Table 3 — L and b values of onion dried with different methods and temperatures

Drying condition	L values	b values
60 °C CIR- Recirculation	92.5 ± 2.7	8.6 ± 0.5
70 °C CIR- Recirculation	93.4 ± 3.2	6.2 ± 0.5
80 °C CIR- Recirculation	88.1 ± 2.4	13.1 ± 1.0
60 °C CIR	93.9 ± 2.8	5.2 ± 2.1
70 °C CIR	92.9 ± 2.3	7.7 ± 0.6
80 °C CIR	89.4 ± 2.1	11.1 ± 1.5
60 °C FAC	83.9 ± 3.5[a]	12.2 ± 0.7[a]
70 °C FAC	91.0 ± 4.0	9.9 ± 0.6[a]
80 °C FAC	93.1 ± 2.7	7.8 ± 0.4

[a]Significantly different value ($P < 0.05$) from other drying methods at same temperature.

Table 4 — Microbial data for aerobic plate counts, coliform counts, and yeast and mold counts of CIR and FAC dried samples (reported as log CFU/10 g dried sample)

		Trial 1			Trial 2			Average 3	
	Fresh	5.24		Fresh	5.54		Fresh	5.39 ± 0.22	
Aerobic plate counts		CIR	FAC		CIR	FAC		CIR	FAC
	60 °C	4.21	4.08	60 °C	3.23	3.41	60 °C	3.72 ± 0.70	3.75 ± 0.47
	70 °C	3.98	4.05	70 °C	3.71	3.36	70 °C	3.85 ± 0.19	3.71 ± 0.49
	80 °C	3.97	4.03	80 °C	3.37	3.39	80 °C	3.67 ± 0.42	3.71 ± 0.45
	Fresh	5.27		Fresh	5.51		Fresh	5.39 ± 0.17	
Coliform counts		CIR	FAC		CIR	FAC		CIR	FAC
	60 °C	3.04	3.95	60 °C	2.40	2.40	60 °C	2.72 ± 0.45	3.18 ± 1.10
	70 °C	2.18	3.93	70 °C	2.40	2.18	70 °C	2.29 ± 0.16	3.05 ± 1.24
	80 °C	1.70	3.00	80 °C	1.00	1.00	80 °C	1.35 ± 0.49	2.00 ± 1.41
	Fresh	4.56		Fresh	4.84		Fresh	4.70 ± 0.20	
Yeast and mold counts		CIR	FAC		CIR	FAC		CIR	FAC
	60 °C	4.16	4.72	60 °C	4.12	4.81	60 °C	4.14 ± 0.03	4.77 ± 0.07
	70 °C	3.83	4.69	70 °C	4.00	4.31	70 °C	3.92 ± 0.12	4.50 ± 0.27
	80 °C	3.44	4.10	80 °C	3.44	4.00	80 °C	3.44 ± 0.00	4.05 ± 0.07

A higher *b* value indicates a higher degree of browning and other color developments caused by enzymatic and nonenzymatic browning reactions. Thus there was more color development in the CIR dried samples at higher temperatures due to the aforementioned reasons. Likewise, FAC drying has less browning at higher temperatures due to a shorter drying time. The higher *b* values of samples dried at 60 and 70 °C with CIR plus air recirculation could be due to increased drying times compared to using CIR drying without air recirculation.

To produce dried onion with a desirable light or white color CIR drying is recommended to dry the product at a mild temperature, such as 70 °C, to take advantage of higher drying rates than observed at 60 °C drying and avoid the increased amount of browning seen in 80 °C drying.

Microbial load reduction. The results of aerobic plate counts (APC) for all of the dried samples were similar (Table 4). For both drying methods, the APC decreased by an average of about 1.7 log from the fresh sample. There was no significant difference between the 2 drying methods nor was there a difference in counts at different drying temperatures. The composition of the surviving population was not determined. The predominant microorganisms in dehydrated spices are aerobic sporeformers (Gray and Pinkas 2001) and it is possible that this was true for the dried onion samples. The APC of the dried product was not significantly different ($P < 0.05$) for any of the drying temperatures or either drying method.

It was difficult to achieve a homogeneous sample of sliced onions to be used for the microbiological testing. The variation between the trials was a result of different amounts and type of microflora represented on each of the samples used. Large standard deviations were a result of averaging the results of the variable trials.

Coliform levels in fresh samples were 5.39 log CFU/10 g dried sample. The coliform count for fresh sample was not significantly different from the APC, suggesting that this group of bacteria dominated the fresh aerobic microflora. As drying temperature increased, coliform counts decreased in the final product. Coliform counts were reduced during the drying process by over 2 logs at 60 °C for both drying methods and by 3 logs at 80 °C. There was no significant difference between the FAC and CIR dried samples at corresponding drying temperatures.

Yeast and mold counts, unlike coliforms, were not accounted for on the APC (Gray and Pinkas 2001). Yeasts and molds do not grow fast enough to appear on APC agar. It is important not to correlate APC to yeast and mold counts. Yeast and mold counts were significantly different for the 2 drying methods. Greater reductions were observed in samples dried in the CIR dryer, which may have been a result of greater heat fluxes from the CIR emitter. The reduction of yeast and mold in the dried samples with either drying method was no greater than 1.4 log.

Conclusions

These experiment results indicate that CIR heating is an effective method for onion drying. Greater drying rates and shorter drying times were seen in CIR drying compared to FAC drying but only at MC greater than 50%. For achieving high quality product and drying rate, a recommended combination of CIR and convection drying is to use CIR to achieve 75% MC and then use convection for later stages of drying. This type of processing would be beneficial for commercial dehydrators who would not have to replace existing equipment to incorporate a CIR unit. The recommended product temperature for CIR drying is 70 and 80 °C. The higher temperature (80 °C) should be used at the beginning of drying to achieve maximum drying rates while product degradation is minimal. The lower temperature (70 °C) should be used for the remainder of drying because it achieves high drying rates but does not have the same adverse effects on quality factors, especially pungency and color, as does continual 80 °C heating. Further research is needed to determine the point at which the temperature should be reduced from 80 to 70 °C. Additional studies are also necessary to determine drying characteristics and quality changes that occur to onions below 10% MC.

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